

The quest for neutrinoless double beta decay: Pseudo-Dirac, Majorana and sterile neutrinos

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In this paper we analyze the neutrinoless double beta decay predictions in some scenarios with admixture of pseudo-Dirac and Majorana neutrinos in the 3 and 3+1 neutrino frameworks. We found that some of the cases can be falsifiable in near-term and future generations of neutrinoless double beta decay experiments even for the normal neutrino mass hierarchy. In the 3+1 framework we consider the sterile neutrino with a mass of the order of 1 eV. The complementarity between cosmological constraints and the future sensitivity for the next generations of the neutrinoless double beta decay searches is exploited.

I. INTRODUCTION

The observation of neutrino oscillations [1–4] implies that neutrinos are massive particles. The fact that the neutrino masses scale is several orders of magnitude smaller than the rest of the fermions of the Standard Model (SM)¹, suggests an extension in which neutrinos are generally expected to be of Majorana type, violating the total lepton number symmetry, such as for example the so-called seesaw mechanism [8–12] which accounts for the observed smallness of neutrino mass relative to that of charged fermions.

The only feasible underground experiments at present that could be able to pin down the Majorana nature of massive neutrinos, namely to prove the electron neutrino Majorana effective mass $|m_{\beta\beta}|$, and thus give information on the violation of the total lepton number symmetry [13] are those searching for neutrinoless double beta $((\beta\beta)_{0\nu})$ -decay [14]: $(A, Z) \rightarrow (A, Z+2) + e^- + e^-$.

Despite intense ongoing efforts, the decay has not been observed yet, but important progresses have been made and especially the data from

the GERDA-I [15] have shown that the claim by Klapdor-Kleingrothaus *et al.* [16] is now strongly disfavored (see [17, 18] for experimental review). On the other hand $|\Delta L| = 2$ processes can be tested in colliders, which opens the possibility to investigate all the elements of the neutrino mass matrix, $M_{\alpha\beta}^\nu$ with $\alpha, \beta = e, \mu, \tau$ (for details see [19]).

In summary the status of lepton and baryon number symmetries remains one of the most interesting unsolved questions in particle physics [20], and neutrinos could very well be Dirac fermions.

II. NEUTRINOLESS DOUBLE BETA DECAY: GENERAL FRAMEWORK

In the 3ν mixing scheme with massive neutrinos, χ_j , being Majorana particles, the $(\beta\beta)_{0\nu}$ -decay can be generated only by the $(V - A)$ charged current weak interaction via the exchange of the three Majorana neutrinos χ_j having masses $m_j \lesssim$ a few eV. The amplitude of the decay is proportional to the so-called Majorana effective mass [21–23]:

$$|m_{\beta\beta}| = \left| m_1 |U_{e1}|^2 + m_2 |U_{e2}|^2 e^{i\lambda_{21}} + m_3 |U_{e3}|^2 e^{i\lambda_{31}} \right|. \quad (1)$$

In eq. (1), U_{ej} , $j = 1, 2, 3$ are the elements of the first row of the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix, U , describing the neutrino mixing [24], and λ_{21} and λ_{31} are the two Majorana CP violation (CPV) phases.

In the standard parametrization of the neutrino

mixing matrix, we have that the elements, U_{ej} , depend only on the reactor and the solar neutrino mixing angles, θ_{13} and θ_{12} . More precisely these elements can be written as:

$$\begin{aligned} |U_{e1}| &= \cos \theta_{12} \cos \theta_{13}, \\ |U_{e2}| &= \sin \theta_{12} \cos \theta_{13}, \\ |U_{e3}| &= \sin \theta_{13}. \end{aligned}$$

Neutrino oscillation data are still compatible with two type of neutrino mass spectra: i) normal ordered, $m_1 < m_2 < m_3$ and ii) inverted ordered,

¹ The most recent cosmological upper bound for the sum of neutrino masses is $\sum m_\nu \leq (0.2 - 0.6) \text{eV}$ [5], this will be complemented by the future sensitivity from the Katrin experiment [6, 7].

$m_3 < m_1 < m_2$. The ordering of the masses determines a peculiar dependence of $|m_{\beta\beta}|$ with respect to the lightest neutrino mass and therefore also with respect to the sum of the light active neutrinos $\sum_i m_i$. Depending on the value of the lightest neutrino mass, $\min(m_j)$, and on the hierarchy of the neutrino masses, the value of $|m_{\beta\beta}|$ can be:

- *quasi-degenerate (QD)*:
 $m_1 \approx m_2 \approx m_3 \approx m_0 \gtrsim 0.1\text{eV}$ gives
 $|m_{\beta\beta}| \gtrsim 0.05\text{eV}$.
- *inverted hierarchical (IH)*:
 $m_3 \ll m_1 < m_2$ so $m_{1,2} \sim \sqrt{\Delta m_A^2}$ gives
 $0.015 \lesssim |m_{\beta\beta}| \lesssim 0.05\text{eV}$.
- *normal hierarchical (NH)*:
 $m_1 \ll m_2 < m_3$ so $m_2 \sim \sqrt{\Delta m_\odot^2}$, $m_3 \sim \sqrt{\Delta m_A^2}$ and so $|m_{\beta\beta}| \lesssim 0.015\text{eV}$.

Further, the minimum for the sum of the neutrino masses compatible with current neutrino oscillation data, namely when the lightest neutrino is massless, is $(\sum_i m_i)_{\min} = 5.87 \times 10^{-2} \text{ eV}$ for NH and $(\sum_i m_i)_{\min} = 9.78 \times 10^{-2} \text{ eV}$ for IH.

The $(\beta\beta)_{0\nu}$ -decay experimental search is therefore compelling due to the enormous impact in determining the nature of massive neutrinos, in constraining the absolute neutrino mass scale as well as in the possibility to test the type of hierarchy for the neutrino masses. So far, current experiments did not observe the decay. From those searches, one can derive lower bounds on the half-lives of the utilized isotopes (see e.g. [18] for a summary). Combining the results by GERDA-I, the Hidelberg-Moscow and IGEX data sets, a limit on the ^{76}Ge half-life was obtained $T_{1/2}^{0\nu}(^{76}\text{Ge}) > 3.0 \times 10^{25} \text{ yr}$ at 90% C.L. [15]. Limits for $T_{1/2}^{0\nu}(^{136}\text{Xe})$ have been set by the EXO-200 and KamLAND-ZEN Collaborations [25, 26].

The next generation of $(\beta\beta)_{0\nu}$ -decay experiments ($\gtrsim 5\text{yr}$), such as GERDA-II (^{76}Ge), SuperNEMO (^{82}Se) CUORE (^{130}Te) and nEXO-200 (^{136}Xe) to name a few, have been planned to reach a sensitivity of $T_{1/2}^{0\nu} \sim (1 - 1.5) \times 10^{26} \text{ yr}$. This is meant to explore the inverted hierarchical region for $|m_{\beta\beta}|$, see the dashed region in Fig. (2). Since $|m_{\beta\beta}|$ scales like $\sqrt{T_{1/2}^{0\nu}}$ one can expect to push down $|m_{\beta\beta}|$ of a factor of 3 or 4 with respect to the present lower bounds. Of course this could be not enough to cover the entire IH region, so at the moment many efforts are focused to reach values for $|m_{\beta\beta}|$ around 10 meV. In this case detector technology plays a crucial role (a

reasonable signal-to-background ratio in the energy interval ΔE of approximately a full width at half maximum (FWHM) around the Q-value is indeed related to possible high resolution detectors) together with the choice of the isotope used in the experiment.

Even though for the current running and near-term $(\beta\beta)_{0\nu}$ -decay experiments will probably be difficult to explore the entire IH region it makes sense, from a theoretical point of view, to consider potential $(\beta\beta)_{0\nu}$ -decay experiments aiming to measure half-lives of the order of 10^{27} yrs or more. This generation of experiments, which we will label in the following as *mega*-experiments for $T_{1/2}^{0\nu} \sim 10^{27}$ yrs and *ultimate*-experiments for $T_{1/2}^{0\nu} \sim 10^{29}$ yrs [27], could test several scenarios involving Majorana neutrinos.

The $(\beta\beta)_{0\nu}$ -decay experimental searches are also complementary to β -decay and cosmology, which has now entered its precision era [28, 29]. The constraints given by the Planck Collaboration on the sum of the light active neutrinos which were obtained from the measurements of the cosmic microwave background (CMB) temperature and lensing-potential power spectra make tantalizing this kind of combined analysis. We will consider as reference value the limit [5]

$$\sum_i m_i \leq 0.23\text{eV} \quad 95\% \text{ C.L.} \quad (2)$$

Future large scale structure surveys like the recently approved EUCLID [30], will allow to constrain $\sum_i m_i$ up to few meV if is combined with the Planck data. We will focus in the following a future sensitivity of $\sum_i m_i \lesssim 0.15 \text{ eV}$.

The complementarity of $|m_{\beta\beta}|$ and the constraints from cosmological observables is starting to be relevant in scenarios or models for neutrino physics². Moreover, the limits from cosmology for the neutrino masses will be complemented by the the Tritium-beta decay experiment KATRIN [6, 7] whose sensitivity for the neutrino mass is expected to be around 0.2 eV.

In this paper we explore testable scenarios in view of the next *mega*- and *ultimate*-generation of $(\beta\beta)_{0\nu}$ -decay searches such as the admixture of pseudo-Dirac and Majorana neutrinos. Along the line with previous works (see e.g. [35]) we explore how the standard predictions for $(\beta\beta)_{0\nu}$ -decay are considerably modified with the most recent neutrino oscillation data [36–38] and especially we investigate which of these scenarios

² See for instance the case of zero textures [31] and neutrino mass sum rules [32–34].

can be experimentally reachable in the *mega*- and *ultimate*-generations even for the NH spectrum (in the standard case in fact strong cancellations could occur leading to a zero $|m_{\beta\beta}|$). Further, it is also known that in the presence of extra light sterile neutrinos, with square mass difference of the order of 1 eV^2 , the $|m_{\beta\beta}|$ is also modified [39, 40]³. We will show how the analysis for $(\beta\beta)_{0\nu}$ -decay and pseudo-Dirac neutrinos changes in the presence of one extra sterile state.

III. LIGHT PSEUDO-DIRAC NEUTRINOS

As it is well known in the three Majorana neutrino framework the $(\beta\beta)_{0\nu}$ -decay amplitude can well be zero in the NH case due to internal cancellations operated by the two Majorana phases spanning values in the range $[0, 2\pi]$. This behavior is not present in the IH case [21]. Further, in the NH scheme, uncertainties in the parameters governing neutrino oscillations, namely the angles and the two square mass differences, determine the existence of a quite large interval for the absolute neutrino mass scale in which $|m_{\beta\beta}|$ can be zero. In the case in which at least one of the light active neutrinos χ_i , $i = 1, 2, 3$ is a Dirac fermion, such field (which is the field with definite mass eigenstate) does not participate in the amplitude of the $(\beta\beta)_{0\nu}$ -decay since it is distinct from its antiparticle and thus it is not possible to Wick-contract the neutrino field operator in order to obtain a neutrino propagator [13, 42, 43].

In this framework neutrinos are usually referred as pseudo-Dirac particles —when the two neutrinos are active-sterile we have the so-called quasi-Dirac neutrino [13] and when they are active-active we have the so called pseudo-Dirac neutrino [44]⁴. In this scenario the prediction for the $(\beta\beta)_{0\nu}$ -decay half-life and thus for $|m_{\beta\beta}|$ can deeply be modified.

In Fig. (1) and (2) we show the dependence of $|m_{\beta\beta}|$ with respect to the sum of the light active states $\sum_i m_i$ in the case of NH and IH respectively if only one of the neutrinos χ_i is a Dirac fermion. In both plots we show the dashed contour which corresponds to the general allowed 3σ region in the standard 3 Majorana neutrino case. The light (Yellow) region corresponds to a 3σ uncertainty in the oscillation parameters while the dark (Gray) area indicates the prediction for $|m_{\beta\beta}|$ for the best fit values in ref. [38]. In the NH case

it is clear from the plots that if χ_1 is a Dirac particle then a lower limit for $|m_{\beta\beta}|$ is found (differently from [35] the current value for θ_{13} determines a non vanishing $|m_{\beta\beta}|$). If instead χ_2 (or χ_3) are Dirac then a cancellation is still possible especially for $\sum_i m_i$ quite near the lower limit given by the current oscillation experiments. The vertical solid line on those plots represents the Planck+WP+BAO limit given in eq. (2) while the vertical dashed line delimiting the shaded area is indicating the sensitivity of the next-generation of cosmological surveys i.e. $\sum_i m_i \lesssim 0.15 \text{ eV}$. The three horizontal bands indicate the GERDA-I limit and the two ranges for $|m_{\beta\beta}|$ corresponding to the *mega*- and *ultimate*- $(\beta\beta)_{0\nu}$ -decay experiments (the intervals for $|m_{\beta\beta}|$ have been computed using the NMEs used in [47]). For the IH scenario in Fig. (2) there is no complete cancellation for the $|m_{\beta\beta}|$ (as in the usual three Majorana neutrino case), so all these scenarios can be falsified in the next generation of $(\beta\beta)_{0\nu}$ -decay experiments.

The case when two of the active states are Dirac particles is represented in the plots in Fig. (3) for NH and in Fig. (4) for IH. Here again the light (Yellow) region corresponds to a 3σ uncertainty in the oscillation parameters while the thick solid line is determined with the best fit values in ref. [38]. The NH cases can all be tested in the *mega*-generation (in the case χ_2 and χ_3 are both Dirac then the interval of $|m_{\beta\beta}| \sim 0$ corresponds to the limit of a massless neutrino). In the case of IH if (χ_1, χ_3) or (χ_2, χ_3) are Dirac fermions then they can be also tested by the *mega*-generation while the case of (χ_1, χ_2) will be very difficult if not impossible to rule out.

IV. EXTRA STERILE NEUTRINOS

In the past decade the framework of 3-neutrino mixing has been challenged by the existence of experimental anomalies found in the i) results of the LSND [48] and MiniBooNE experiments [49] ii) re-analyses of the short baseline (SBL) reactor neutrino oscillation data using newly calculated fluxes of reactor $\bar{\nu}_e$, which detect a “disappearance” of the reactor $\bar{\nu}_e$ (“reactor neutrino anomaly”) [50, 51] iii) results of the calibration experiments of the radio-chemical Gallium solar neutrino detectors GALLEX and SAGE (“Gallium anomaly”)[52, 53] —for a review see e.g. [54]. These anomalies could be explained enlarging the field content in the neutrino sector with one or more massive neutrinos with a square mass difference around 1 eV^2 .

³ For the influence of a keV sterile neutrino on the neutrinoless double beta decay effective mass see [41]

⁴ For examples of models see for instance [35, 45, 46].

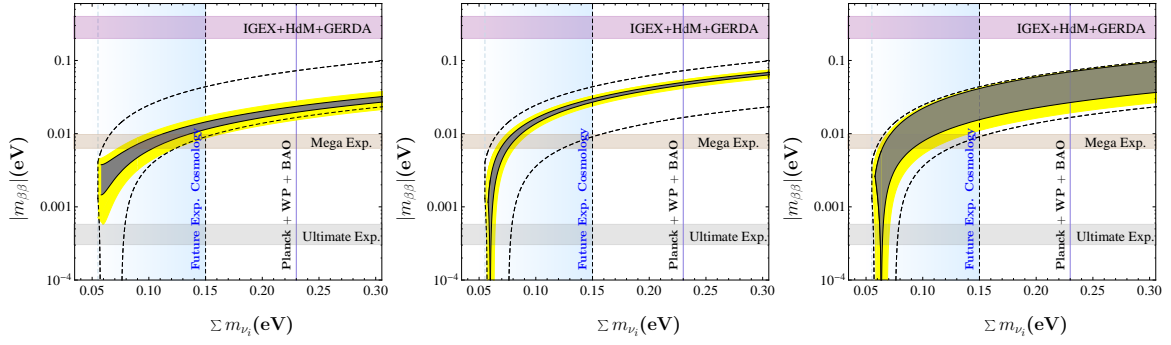


Figure 1. Plots for $|m_{\beta\beta}|$ vs $\sum_i m_i$ for the NH case in the case in which respectively, from the left to the right, χ_1 or χ_2 or χ_3 is a Dirac fermion and therefore the related contribution is not present in $(\beta\beta)_{0\nu}$ -decay amplitude. The light (Yellow) region corresponds to a 3σ uncertainty in the oscillation parameters while the dark (Gray) area indicates the prediction for $|m_{\beta\beta}|$ for the best fit values given in [38]. The solid vertical line corresponds to the Planck constraint in eq. (2). The shaded area for $\sum_i m_i \lesssim 0.15$ eV indicates the future cosmological sensitivity. The dashed contour indicate the standard predictions with three Majorana active neutrinos.

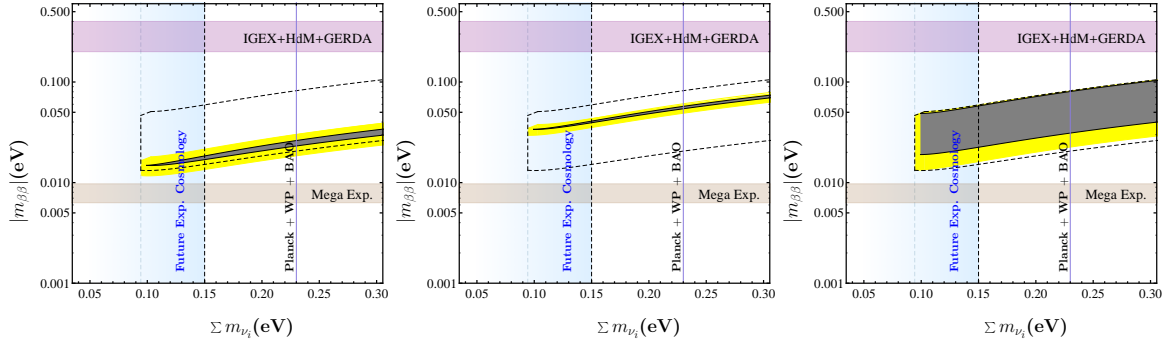


Figure 2. Plots for $|m_{\beta\beta}|$ vs $\sum_i m_i$ for the IH case in the case in which respectively, from the left to the right, χ_1 or χ_2 or χ_3 is a Dirac fermion. The dashed contour indicates the standard predictions with three Majorana active neutrinos. The same colors of Fig. (1) are used for the allowed regions.

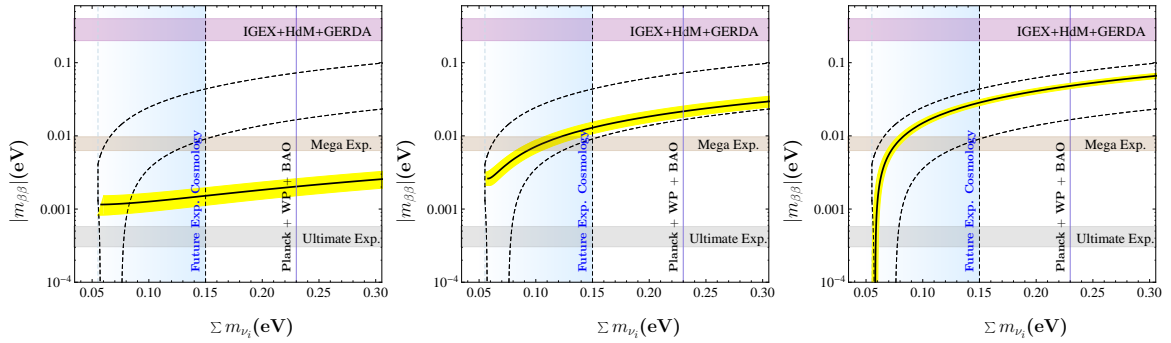


Figure 3. Plots for $|m_{\beta\beta}|$ vs $\sum_i m_i$ for the NH case in the case in which respectively, from the left to the right, (χ_1, χ_2) or (χ_1, χ_3) or (χ_2, χ_3) are Dirac fermions. The same colors of Fig. (1) are used for the allowed regions.

It is worth stressing that if this extra sterile state exists it would be completely thermalised in the early universe through mixing and scattering processes. However this is not confirmed by recent cosmological results which actually seem to disfavour these scenarios since such sterile state(s) would lead to a too strong suppression of structure formation. Nevertheless sterile states with 1 eV mass, as indicated by SBL data, are still possible

if either some neutrino-antineutrino asymmetry is at work in order to inhibit the sterile neutrino production in the early universe or a modification of the cosmological model is provided. In any case a mechanism preventing a full thermalization is needed (see [55] and references therein). It has been noticed in some works (see e.g. [39, 40]) that if one or two sterile Majorana neutrinos exist then they deeply modify the predictions for the $(\beta\beta)_{0\nu}$ -

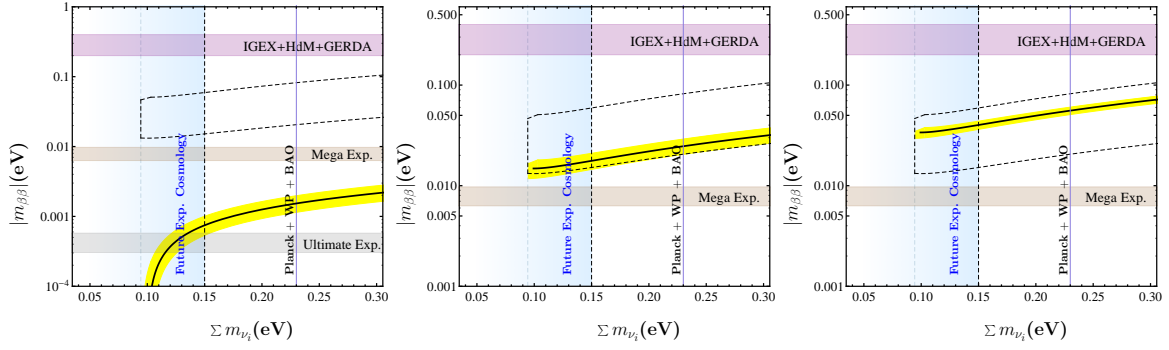


Figure 4. Plots for $|m_{\beta\beta}|$ vs $\sum_i m_i$ for the IH case in the case in which respectively, from the left to the right, (χ_1, χ_2) or (χ_1, χ_3) or (χ_2, χ_3) are Dirac fermions. The same colors of Fig. (1) are used for the allowed regions.

decay. In the simplest scheme with one extra sterile neutrino, the so called 3 + 1 scheme, the matrix which describes neutrino mixing is now a 4×4 unitary matrix which can be written as:

$$U = O_{34}V_{24}O_{23}O_{14}V_{13}V_{12} \times \text{diag}(1, e^{i\lambda_1}, e^{i\lambda_2}, e^{i\lambda_3}), \quad (3)$$

where O_{ij} and V_{kl} are real and complex rotations in $i - j$ and $k - l$ planes respectively, while λ_1 , λ_2 and λ_3 are three CPV Majorana phases. In the effective Majorana mass $|m_{\beta\beta}|$ only the elements of the first row of the neutrino mixing matrix are

relevant and their expressions can be written in a completely generic way as:

$$\begin{aligned} U_{e1} &= c_{12}c_{13}c_{14}, & U_{e2} &= e^{i\alpha/2}c_{13}c_{14}s_{12}, \\ U_{e3} &= e^{i\beta/2}c_{14}s_{13}, & U_{e4} &= e^{i\gamma/2}s_{14}, \end{aligned} \quad (4)$$

where we have used the standard notation $c_{ij} \equiv \cos \theta_{ij}$ and $s_{ij} \equiv \sin \theta_{ij}$ and α, β and γ are a definite combination of the phases appearing in U . The element U_{e4} , and thus the angle θ_{14} , describes the coupling of fourth neutrino χ_4 to the electron in the weak charged lepton current. The $|m_{\beta\beta}|$ in this framework has the form:

$$|m_{\beta\beta}| = \left| m_1|U_{e1}|^2 + m_2|U_{e2}|^2 e^{i\alpha} + m_3|U_{e3}|^2 e^{i\beta} + m_4|U_{e4}|^2 e^{i\gamma} \right|. \quad (5)$$

Depending on the neutrino mass hierarchy, we will have:

- NH:

$$\begin{aligned} m_1 &\equiv m, & m_2 &= \sqrt{m^2 + \Delta m_{21}^2}, \\ m_3 &= \sqrt{m^2 + \Delta m_{21}^2 + \Delta m_{31}^2}, & m_4 &= \sqrt{m^2 + \Delta m_{41}^2} \end{aligned}$$

- IH:

$$\begin{aligned} m_1 &\equiv \sqrt{m^2 + \Delta m_{31}^2}, & m_2 &= \sqrt{m^2 + \Delta m_{21}^2 + \Delta m_{31}^2}, \\ m_3 &= m, & m_4 &= \sqrt{m^2 + \Delta m_{41}^2} \end{aligned}$$

In this section we want to illustrate the predictions for $|m_{\beta\beta}|$ in the scenario with one extra Majorana sterile state, χ_4 , and three light active states χ_1, χ_2, χ_3 which can be pseudo-Dirac or Majorana particles. We will consider as reference value for $\sin \theta_{14}$ and Δm_{41}^2 the result obtained in

the global analyses performed in [56]⁵:

$$\sin \theta_{14} = 0.15, \quad \Delta m_{41}^2 = 0.93 \text{ eV}^2 \quad (6)$$

⁵ For another global fit see [57]. Here we only give an example of how the $|m_{\beta\beta}|$ is modified in the scenario of pseudo-Dirac neutrinos and one Majorana sterile state.

In Fig. (5) we show the $|m_{\beta\beta}|$ versus the lightest neutrino mass m_ν^{light} in the standard 3ν framework. In this case for both NH and IH the $|m_{\beta\beta}|$ can vanish. Moreover for small absolute masses, namely for $m_\nu^{light} < 0.01$ eV and $|m_{\beta\beta}| < 0.01$ eV only IH is possible therefore only the *mega*- and *ultimate*-generation of $(\beta\beta)_{0\nu}$ -decay experiments might constrain this scenario.

As in the previous section we analyze first of all the cases in which one of the lightest states χ_1 , χ_2 or χ_3 is a Dirac neutrino. The results are shown in Fig. (6) and Fig. (7) for NH and IH respectively. In both plots we consider a 3σ uncertainty in the oscillation parameters which corresponds to the light shaded region while the colour shaded area determines the allowed range for the best fit values of ref. [38]. As it is clear from the plots strong cancellations could be at work in $|m_{\beta\beta}|$ for

most of the cases both in the NH and in IH. In the NH case the intervals for the lightest mass where a complete cancellation occurs are in the region $m_\nu^{light} \equiv m_1 > 0.01$ eV. In the IH scheme instead the cancellation can be realized for smaller, or even zero, $m_\nu^{light} \equiv m_3$. There is only one case, e.g. when χ_2 is the Dirac particle, where for any value of m_3 $|m_{\beta\beta}| \gtrsim 5$ meV. In this case $|m_{\beta\beta}|$ has a similar behaviour with respect to the standard IH three neutrino case.

More interestingly if a couple of the lightest states are Dirac fermions than of course in some cases the relative cancellations among the different terms are less effective so in the NH with Dirac (χ_1, χ_2) and in IH in the cases with (χ_1, χ_2) and (χ_2, χ_3) $|m_{\beta\beta}|$ could well be test in the next generation of experiments like GERDA-II, CUORE, etc. This is depicted in Fig. (8) and (9).

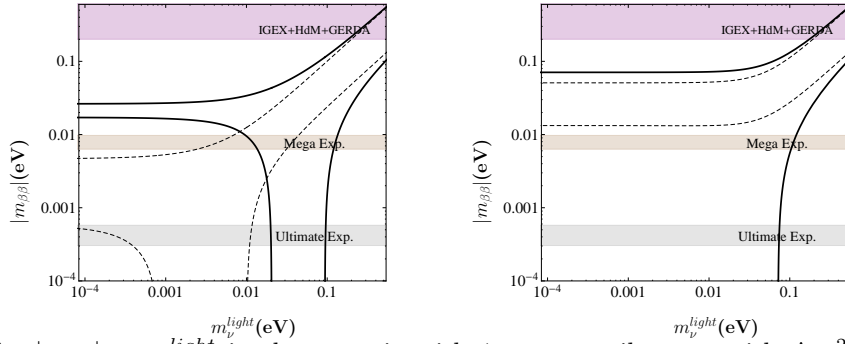


Figure 5. Plots for $|m_{\beta\beta}|$ vs m_ν^{light} in the scenario with 1 extra sterile state with $\Delta m_{SBL}^2 = 0.93 \text{eV}^2$ and $\sin\theta_{14} = 0.15$ for NH (left panel) and IH (right panel). The dotted contours define the allowed range for $|m_{\beta\beta}|$ in the 3ν framework. See text for further details.

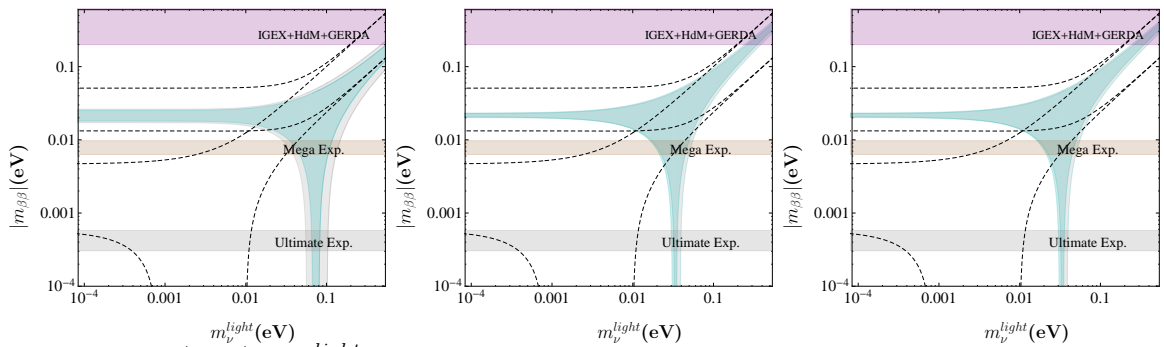


Figure 6. Plots for $|m_{\beta\beta}|$ vs m_ν^{light} for the NH case in the presence of one extra sterile neutrino in the case in which respectively, from the left to the right, χ_1 or χ_2 or χ_3 are Dirac fermions. The light (Gray) shaded area is the 3σ allowed range given by oscillation data while the darker (Blue) shaded area is obtained from the best fit values in [38]. The dashed contour corresponds to the predictions for the 3ν case.

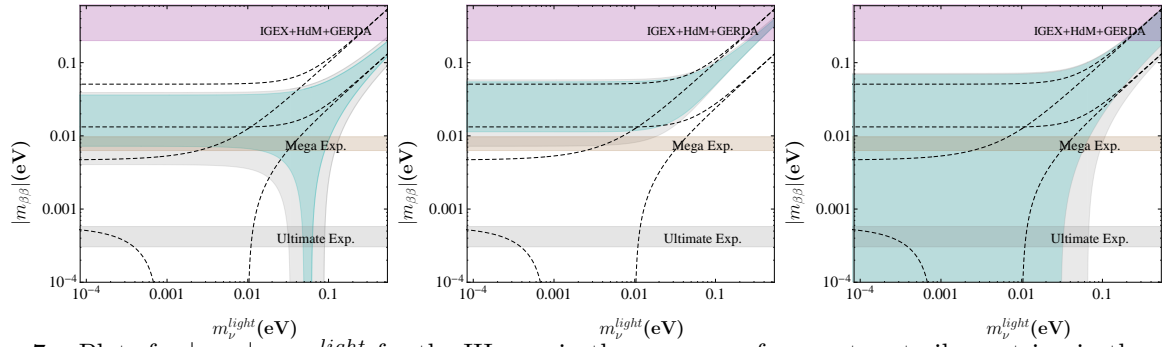


Figure 7. Plots for $|m_{\beta\beta}|$ vs m_{ν}^{light} for the IH case in the presence of one extra sterile neutrino in the case in which respectively, from the left to the right, χ_1 or χ_2 or χ_3 are Dirac fermions. The light and darker shaded areas are given as in Fig. 6.

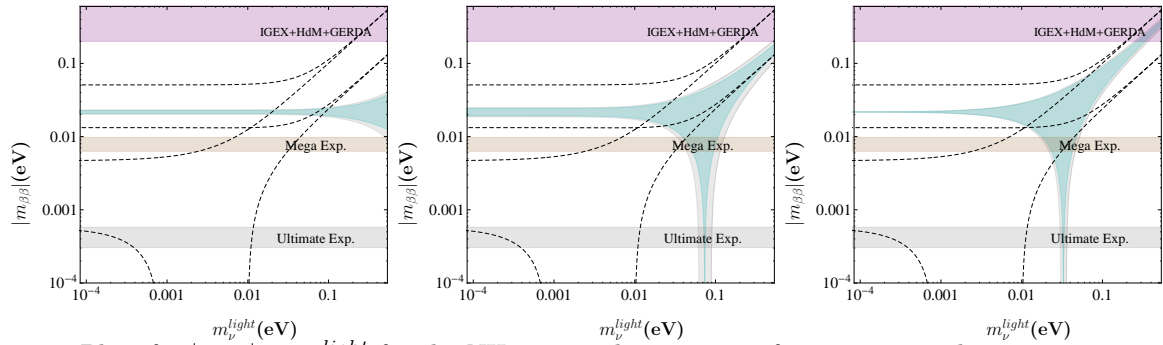


Figure 8. Plots for $|m_{\beta\beta}|$ vs m_{ν}^{light} for the NH case in the presence of one extra sterile neutrino state and in the case in which respectively, from the left to the right, (χ_1, χ_2) or (χ_1, χ_3) or (χ_2, χ_3) are Dirac fermions. The light and darker shaded areas are given as in Fig. 6.

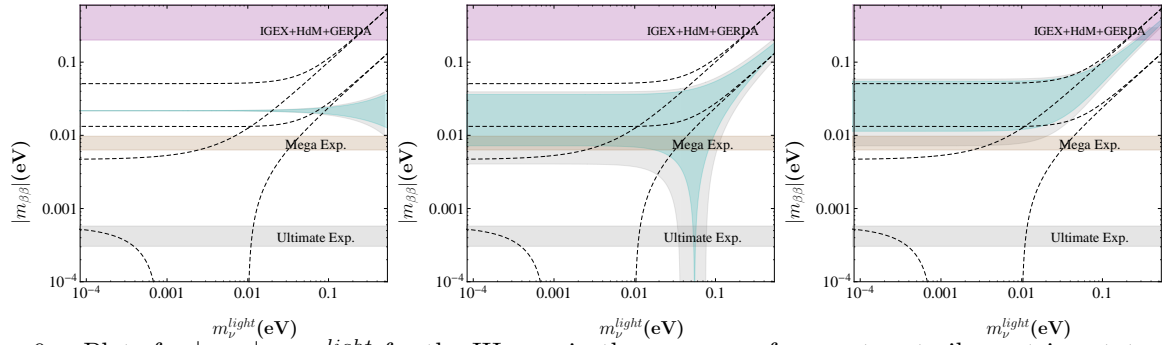


Figure 9. Plots for $|m_{\beta\beta}|$ vs m_{ν}^{light} for the IH case in the presence of one extra sterile neutrino state and in the case in which respectively, from the left to the right, (χ_1, χ_2) or (χ_1, χ_3) or (χ_2, χ_3) are Dirac fermions. The light and darker shaded areas are given as in Fig. 6.

V. DISCUSSION

The current and near term neutrinoless double beta decay $((\beta\beta)_{0\nu}$ -decay) experiments will be able to explore the region for $|m_{\beta\beta}| \gtrsim 0.01$ eV. Hopefully with experiments such as GERDA-II, CUORE, nEXO etc. most of this region will be investigated but if the decay is not observed new experimental efforts will be required. From the theoretical point of view, it is also necessary to

understand which phenomenological frameworks could be tested in the next generation of $(\beta\beta)_{0\nu}$ -decay experiments and also with the future *mega*- and *ultimate*-generations. In particular, it makes sense to investigate which scenarios for the NH spectrum can be experimentally reachable in the *mega*- and *ultimate*-generations, since in the standard three Majorana neutrino framework a complete cancellation can occur.

In this paper we have analyzed the case in which

one or two active neutrinos are Dirac particles for both NH and IH. We found that due to narrow 3σ range for θ_{13} most of the cases we analyzed with one Dirac neutrino, could be falsifiable in the $(\beta\beta)_{0\nu}$ -decay *mega*-generation since a complete cancellation not always occurs. In fact for the NH case there is no cancellation when the neutrino χ_1 is Dirac, see the plot on the left of Fig. (1). On the opposite, if a complete cancellation is realized, this occurs in a region where the lightest state is almost massless, see the plot in the center and on the right of Fig. (1). In the case of two Dirac neutrinos, a cancellation occurs only when the Dirac neutrinos are (χ_2, χ_3) , see the plot in the right side of Fig. (3).

In the second part of the paper we have analyzed the allowed region for $(\beta\beta)_{0\nu}$ -decay in the presence of pseudo-Dirac neutrinos together with an extra sterile neutrino state with mass of the order of 1 eV, as hinted by a number of anomalies arising in short baseline neutrino oscillation experiments. In this case if one of the active state is Dirac then in all the cases we analyzed but one, strong cancellations can occur. However, it is notable that for NH, these scenarios are considerably different from the standard three-neutrino case because the interval for the lightest neutrino mass in which the $|m_{\beta\beta}|$ is zero is different. If instead two of the active states are Dirac fermions then the situation is more favorable and some cases are in the range of the next generation experiments. In summary, it

makes sense from a theoretical perspective to analyze different scenarios for the nature of massive neutrinos that could be tested through terrestrial experiments. This means not only neutrinos as pure Dirac or pure Majorana particles but also the possibility that both natures coexist, even if from the theoretical point of view is less appealing.

VI. ACKNOWLEDGMENTS

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VII. APPENDIX

In this appendix for completeness we show the $|m_{\beta\beta}|$ versus the sum of the three light active states in the case one extra sterile neutrino is added, see Fig. 10. We show as well $|m_{\beta\beta}|$ vs the sum of the active neutrinos in the pseudo-Dirac scenarios considered in Section IV. In Figs. 11, 12, 13 and 14 the light shaded regions correspond to the 3σ uncertainty in the oscillation parameters while the darker shaded area determines the allowed range for the best fit values of ref. [38].

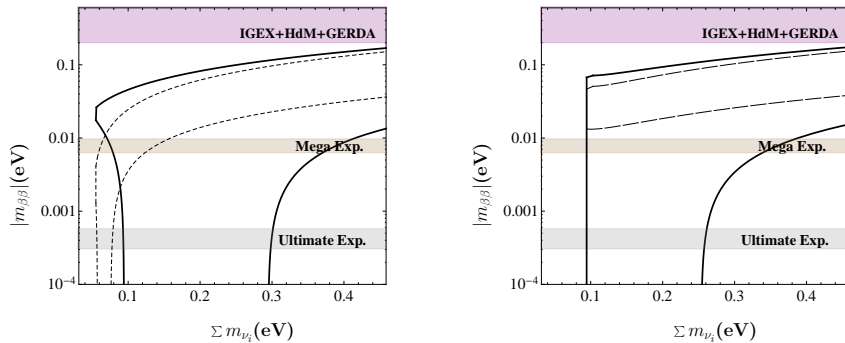


Figure 10. Plots for $|m_{\beta\beta}|$ vs $\sum_i m_i$ in the 3+1 scenario i.e. with one extra sterile state with $\Delta m_{SBL}^2 = 0.93 eV^2$ and $\sin \theta_{14} = 0.15$ for NH (left panel) and IH (right panel). The dotted contours define the allowed range for $|m_{\beta\beta}|$ in the 3ν framework.

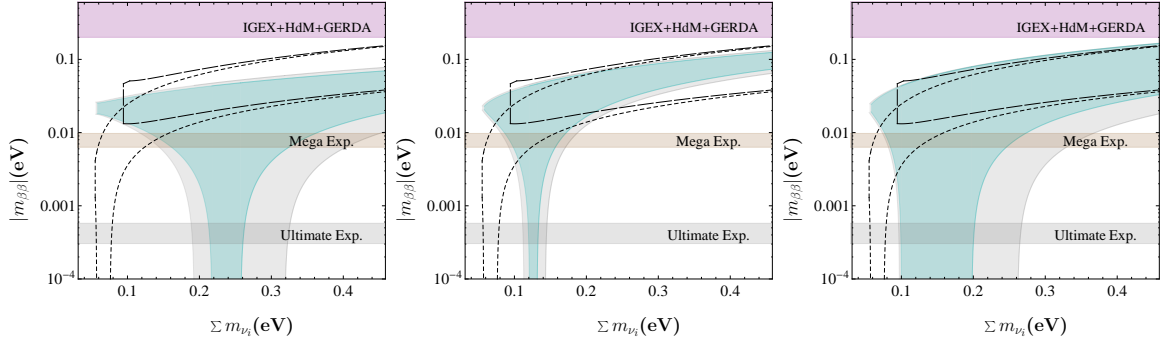


Figure 11. Plots for $|m_{\beta\beta}|$ vs $\sum_i m_i$ in the 3+1 scenario for the NH case in the case in which respectively, from the left to the right, χ_1 or χ_2 or χ_3 are Dirac fermions. The light (Gray) shaded area is the 3σ allowed range given by oscillation data while the darker (Blue) shaded area is obtained from the best fit values in [38]. The short (long) dashed contours correspond to the predictions for the 3ν case.

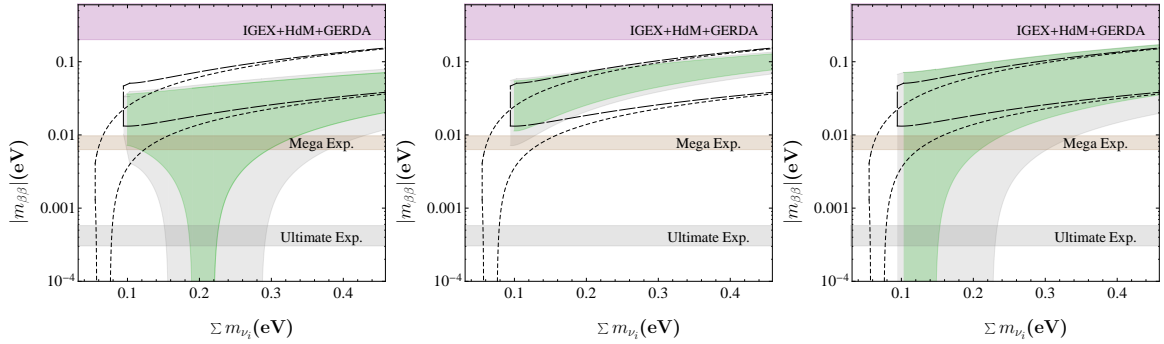


Figure 12. Plots for $|m_{\beta\beta}|$ vs $\sum_i m_i$ for the IH case in the presence of one extra sterile neutrino in the case in which respectively, from the left to the right, χ_1 or χ_2 or χ_3 are Dirac fermions. The light (Gray) and darker (Green) shaded areas indicate the allowed range for the 3σ and best fit values given in [38].

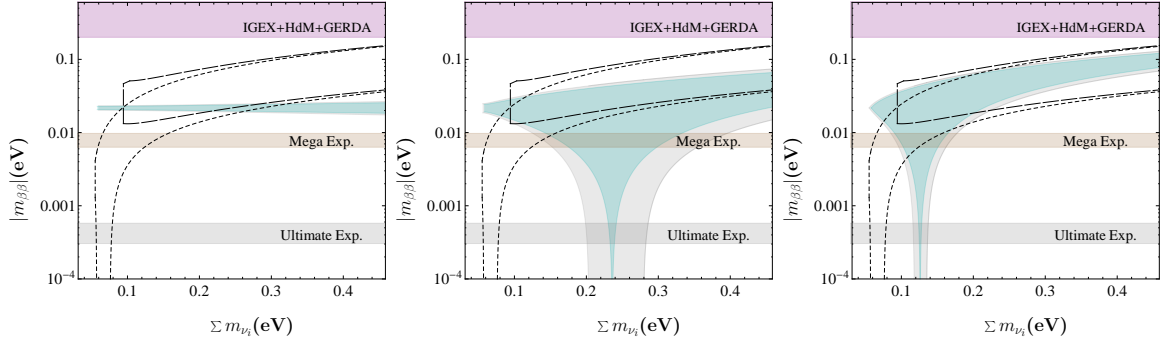


Figure 13. Plots for $|m_{\beta\beta}|$ vs $\sum_i m_i$ for the NH case in the presence of one extra sterile neutrino state and in the case in which respectively, from the left to the right, (χ_1, χ_2) or (χ_1, χ_3) or (χ_2, χ_3) are Dirac fermions. The light (Gray) and darker (Blue) shaded areas are given as in Fig. 11.

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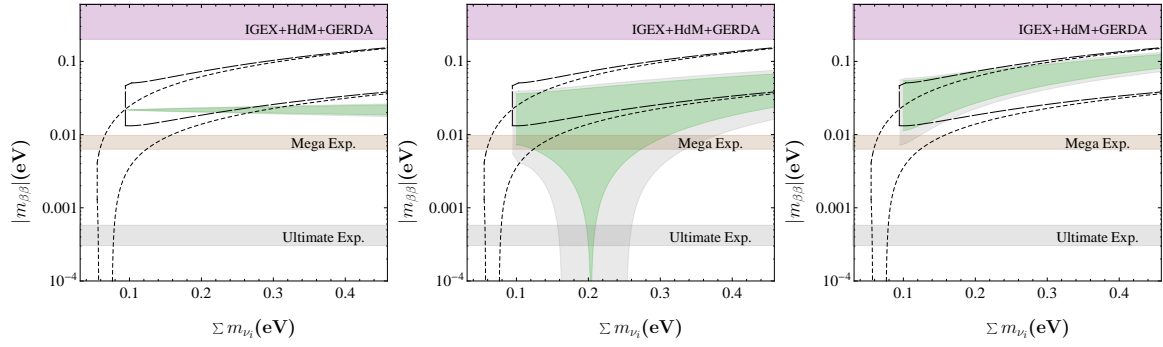


Figure 14. Plots for $|m_{\beta\beta}|$ vs $\sum_i m_i$ for the IH case in the presence of one extra sterile neutrino state and in the case in which respectively, from the left to the right, (χ_1, χ_2) or (χ_1, χ_3) or (χ_2, χ_3) are Dirac fermions. The light (Gray) and darker (Green) shaded areas are given as in Fig. 12.

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